"On the Changes of Thermoelectric Power produced by Magnetisation, and their Relation to Magnetic Strains." By SHELFORD BIDWELL, M.A., Sc.D., F.R.S. Received April 11,—Read April 28, 1904.

Summary.

It is well known that magnetisation generally produces a change both in the thermoelectric quality of a magnetisable metal, and also in its linear dimensions. In an article published in October, 1902,* I directed attention to the remarkable qualitative correspondence which appeared in several cases to exist between the two classes of phenomena, and the experiments which form the subject of the present paper were undertaken with the view of investigating their apparent relation. Some of the results were of an unexpected character. The accepted statements regarding certain thermoelectric effects to which in this connection special importance was attached, turn out to be at least not generally true, and, as far as my own observations go, altogether erroneous. Several experimenters appear to have been misled by regarding as unmagnetised a piece of metal which either retained some permanent magnetism or was continuous with the piece subjected to magnetisation. What they in fact observed was not the thermoelectric power of magnetised with respect to unmagnetised metal, but that of more strongly magnetised with respect to less strongly magnetised; and the effects may be, as will appear, directly opposite in the two cases. Probably also mistakes have arisen from the assumption that for a lengthened period the electromotive forces in the circuit underwent no changes other than those due to magnetisation. It is hardly possible to keep the temperatures throughout so nearly constant as to avoid gradual changes of electromotive force considerably greater than those which it is desired to measure. In my own work careful precautions were taken against both these sources of error; before every observation the metal was demagnetised by reversals, and the galvanometer reading for no magnetisation was noted.

Although, as mentioned, some of the chief grounds which formed the basis of my conjecture as to a possible relation between the thermoelectric and the strain effects have disappeared, strong evidence is nevertheless forthcoming, that for iron and nickel there is such a relation, and that not merely qualitative but quantitative. As regards one important detail there is an unexplained inconsistency in the behaviour of the two metals, but the coincidences observed in both cases are too numerous and too varied to be the result of accident.

Iron.—For iron, when allowance is made for the purely mechanical

* 'Ency. Brit.,' vol. 30, p. 449, article "Magnetism."

compression due to magnetisation,* the change of thermoelectric power appears to be proportional to the change of length. Change of thermoelectric power expressed in microvolts is nearly (and perhaps under perfect experimental conditions would be exactly) numerically equal to the "corrected" change of length in ten-millionths multiplied by a factor which is constant for the same specimen in the same physical condition, but differs for different specimens, and for different physical conditions of the same specimen. For my sample of pure iron when in a free state, the factor giving the best agreement is 183×10^{-5}; for a sample of good commercial iron it is $63{\cdot}6 \times 10^{-5}$; and for the pure iron stretched by a load of 1620 kilogrammes per sq. cm. its value is 112×10^{-5}. The curves expressing the relations of thermoelectric power and of change of length to magnetising force are not indeed exactly coincident, as may be seen by reference to figs. 4 and 5; but since identical specimens of the metal were not used in the two sets of experiments, while the conditions were necessarily somewhat different, the divergencies cannot but be regarded as very small; sometimes, indeed, they hardly exceed the limits of experimental error. The thermoelectric and the elongation curves for iron appear to be similarly influenced by the physical condition of the metal; I have shown† that the elongation curve is lower for annealed than for unannealed iron, and that tensile stress also lowers the curve; the same is the case with the curves of thermoelectric power. The strength of the magnetic field at which, as indicated by the corrected curve, there would be no change of length under tensile stress, appears to be just the same as that at which the thermoelectric force becomes zero; when this strength is exceeded, retraction occurs instead of elongation, and a simultaneous reversal occurs in the direction of the thermoelectric force. Unlike previous experimenters I find that when the iron is free from tensile stress the direction of the thermoelectric force is never reversed by magnetisation, even in fields up to 1600 C.G.S. units; neither does the curve of change of length when "corrected" for mechanical stress ever cross the horizontal axis.

Nickel.—Partly on account of the smaller magnetic susceptibility of nickel, and partly in consequence of the relatively great changes of length which that metal undergoes when longitudinally magnetised, the correction for mechanical stress is almost negligible, averaging less than 3 per cent. for fields up to 1200. Here, too, the forms of the curves for change of length and change of thermoelectric power in relation to H are strikingly alike (see fig. 7), the correspondence being even closer than in the case of iron. For a specimen of pure nickel the increase of thermoelectric power in microvolts, due to magnetisa-

* It is a disputed point whether there actually is any such compression. The subject is discussed later.

† 'Roy. Soc. Proc.,' vol. 55, p. 228, 1894; vol. 47, p. 469, 1890.

tion in any field up to 1600 (the strongest reached), was found to be about equal numerically to the retraction in ten-millionths multiplied by 145×10^{-5}. The curves for two pieces of an impure nickel also exhibit general similarity of form, but since the dimensional ratios (ratio of length to cross section) of the two pieces are very different, the curves are not strictly comparable. The changes of thermoelectric force are, like the changes of length, much greater for nickel than for iron. Tensile stress produces, as in iron, corresponding variations in the two classes of curves. The effect of tension upon the magnetic retraction of nickel is, as I have shown in a former paper,* not so simple as in the case of iron. In weak fields the contraction is diminished by tension; in fields of more than about 150 units the contraction is increased by tensile stress up to a certain critical value of the stress depending upon the strength of the field, and diminished by greater tension. Thus it happens that the retraction curves for a wire loaded with two different weights may cross each other. In one of my published experiments the retraction curves for a nickel wire carrying loads of 420 and of 980 kilogrammes per sq. cm. crossed when H reached 220. With nearly the same loads, the two curves of thermoelectric force also crossed, though in a weaker field, H being only 150. Wire of the same quality was used in both experiments, but in the first it was hard, while in the second it was annealed, which may or may not be the reason of the difference. In any case, it is interesting to find this complex and unexpected phenomenon qualitatively reproduced by the thermoelectric curves.

The anomaly above referred to consists in the fact that the direction of the thermoelectric force due to magnetisation is the same for nickel as for iron, whereas length is affected oppositely in the two metals, iron being extended, nickel contracted.

Cobalt.—For cobalt I have not succeeded in finding any relation between the thermoelectric and dimensional changes attending magnetisation. The thermoelectric curve somewhat resembles that for nickel, but it is much lower. The strain curve is opposite in character to that of iron; in weak fields the metal contracts, in strong fields it is elongated.

Nomenclature.

When the direction of the thermoelectric current between two metals, A and B, was from A to B through the hot junction, it was formerly the custom to say that A was positive to B, and B negative to A; bismuth, for example, was said to be thermoelectrically positive to antimony. Of late years this custom has to a large extent been reversed, and the terminology is at present in an unsettled condition. Following what I believe to be the best modern authorities, I shall in

* 'Roy. Soc. Proc.,' vol. 47, p. 474, 1890.

this paper speak of a metal A as being positive to B when the thermo-current passes from A to B through the *cold* junction, or from B to A through the hot. The thermoelectric power of bismuth with respect to lead is thus negative, while that of antimony is positive.

Previous Researches.

The results of my own experiments compel me to dissent from some of the conclusions which have been reached by other workers. The discrepancies noticed are, I think, in most cases due to the fact already referred to, that the thermoelectric behaviour of weakly magnetised with respect to strongly magnetised iron and impure nickel may be very different from that of the unmagnetised with respect to the magnetised metal.

The earliest observations of the effects of magnetisation upon thermo-electric power are those of Professor W. Thomson (Lord Kelvin), who in 1856* announced that magnetisation rendered iron and steel positive to the unmagnetised metals (the thermo-current passing from unmagnetised to magnetised through hot), while in nickel the opposite effect was produced. The latter statement, though it has never, I believe, been disputed, is beyond doubt erroneous. Iron, steel, and nickel, when free from mechanical stress, all become more positive when magnetised.

The effects of tension and magnetisation upon the thermoelectric quality of iron have been investigated by Ewing,† who found that "the presence of load diminishes the general thermoelectric effect of magnetisation, and finally reverses it when the load is great." Although this happens to be a correct statement of the facts, it is, I venture to think, exceedingly doubtful whether a genuine reversal was actually attained in a field of only 17 units, the strongest applied by Ewing, even with a load on the wire of 4000 kilogrammes per sq. cm. From the description of the apparatus (p. 368) it appears that the piece of wire regarded as unmagnetised was continuous with the magnetised portion, the hot junction separating the magnetised from the unmagnetised iron being just outside the magnetising coil.

Chassagny‡ was the first to announce that the increase of thermo-electric power due to magnetisation reaches a maximum in a moderate field and diminishes in stronger fields. In his experiment the electro-motive force was greatest in a field of 55 units, falling to about half its maximum value in a field of 200.

In a similar experiment by Houllevigue§ a maximum was indicated at $H = 42$, and at $H = 352$ the increase of thermoelectric force due

* Bakerian Lecture, 'Phil. Trans.,' 1856, p. 722.

† 'Phil. Trans.,' 1886, p. 361.

‡ 'C. R.,' vol. 116, p. 977, 1893.

§ 'Journ. de Physique,' vol. 5, p. 53, 1896.

to magnetisation had apparently become zero. His paper contains no record of an actual reversal of the force in stronger fields, though the probability of such reversal is suggested. My experiments, which were made with several different specimens of iron, show no approach to zero in fields nearly five times as strong as that mentioned. As regards the behaviour of steel, Houllevigue's results are at variance both with those of W. Thomson and with my own.

Mr. E. Rhoads* has given an account of two thermoelectric experiments, one of which was made with iron, the other with nickel, his work having been undertaken "in looking for some property of iron that would vary with the magnetisation in the same way as the length." After referring to the experiments of Chassagny, and to those of Houllevigue "who found that the diminution [of thermoelectric force] continues in higher fields, and that a reversal actually takes place," he remarks that "this suggests change of length, and made me wish to work out the cyclic curve for comparison with it." The cyclic curve which he obtained exhibits hysteresis, and bears a general resemblance to one given for change of length, though the latter is not carried beyond $H = 90$. The thermoelectric curve for iron is represented as crossing the axis of H at $H = 400$, continuing to fall in an almost straight line up to $H = 500$, the strongest field applied. Rhoads considers that it agrees with the curve for change of length when the latter is corrected for "Maxwell's stress" (which is given as $B^2/4\pi$) being apparently unaware of the fact demonstrated by More, and afterwards by Klingenberg, that the corrected curve never crosses the horizontal axis. The thermoelectric curve for nickel is shown in Rhoads's diagram as lying, like the curve for change of length, below the horizontal axis (in agreement with Thomson's experiment), while for iron, both the thermoelectric and the corrected length curves are above the axis. "The two properties," he says, "turn out to be related in the opposite sense in the two metals." As regards form, the nickel curves for change of thermoelectric power and change of length are of the same character, even though, as is remarked, they are not strictly comparable, being made with very different specimens. No mention is made of Maxwell's stress in relation to nickel.

Mechanical Stress due to Magnetisation.

Before describing the experiments it is desirable to discuss briefly the controverted question of compressive stress which has such an important bearing upon the results. In a paper† on the changes of

* 'Physical Review,' vol. 15, p. 321. This paper was published about 2 months later than my article above referred to. My experiments were begun before I had heard of Mr. Rhoads's work.

† 'Phil. Trans.,' vol. 179, p. 216, 1888.

dimensions due to magnetisation, published in 1888, I wrote: "One of the influences tending to produce retraction must certainly be of a purely mechanical nature. Suppose a uniformly magnetised rod to be transversely divided through the middle. The two halves, if placed end to end, will be held together by their mutual attraction, pressing against each other with a certain force per unit of area, which can be measured by the weight necessary to tear one half from the other. The same pressure will exist between any two portions of the rod separated by any possible cross section, and a certain longitudinal contraction of the rod will be the consequence. If, now, the rod, having been first demagnetised, be placed in a vertical position upon a fixed base, and loaded at the upper end with a weight equal to the greatest it could support when magnetised, it will undergo the same contraction as before, the [compressive] stresses being equal in the two cases." It is pointed out that in the latter case the contraction is expressed as a fraction of the original length by P/M, M being Young's modulus, and P the load, both in grammes weight per square centimetre. Assuming the magnetisation to be such that the divided rod can just support a weight of P grammes per square centimetre, it is inferred that the contraction due to the mechanical effect of magnetisation would again be P/M, and it is shown that this accounts for a part only of the observed change of length. In an earlier paper* it was calculated that P, the weight per square centimetre supported in the field H, was equal to $(2\pi I^2 + HI)/g$, I being the magnetisation, and g the intensity of gravity. This expression (which is equivalent to $(B^2 - H^2)/8\pi g$), is applicable when the magnetic metal is magnetised longitudinally and uniformly by an external field, as was approximately the case in the experiments with which the present paper is concerned, where the wires were placed in the axis of an independent magnetising coil. For the special case in which each half of the divided rod is surrounded by a separate magnetising coil wrapped tightly around it, another term, $H^2/8\pi$, must be added for the mutual action of the two coils, and we shall have

$$Pg = 2\pi I^2 + HI + \frac{H^2}{8\pi} = \frac{(4\pi I + H)^2}{8\pi} = \frac{B^2}{8\pi}.$$

Also for a permanent ring-magnet, in which there is no magnetic force H,

$$Pg = 2\pi I^2 = 2\pi \left(\frac{B}{4\pi}\right)^2 = \frac{B^2}{8\pi}.$$

It should be noticed that since, except in very strong fields, H^2 is negligible in comparison with B^2, the force in the first case considered

* 'Roy. Soc. Proc.,' vol. 47, p. 486, 1886.

may generally without sensible error be taken as $B^2/8\pi$, instead of $(B^2 - H^2)/8\pi$ or $2\pi I^2 + HI$.*

In the year 1895 it was pointed out by More,† who was apparently ignorant of what I had written on the subject, though he was certainly familiar with most of my work, that the change of length attending magnetisation must be due to several causes, among which are the mechanical stresses created in the rod. "The first of these mechanical stresses is the tractive force of the magnet, and is measured by $B^2/8\pi$." This force, he remarks, tends always to contract the rod, and for high intensities becomes one of the most important factors in the observed changes of length. In plotting his curves (in which abscissæ are I instead of H) he makes "correction for the contraction due to the $B^2/8\pi$ force. This correction is obtained from the formula

$$\frac{\delta l}{l} \times 10^7 = \frac{B^2/8\pi}{M},$$

where M is the modulus of elasticity. The effect of this correction is to make the elongation much greater for a given intensity. The maximum value of the elongation is more than twice as great as the observed maximum, and the greatest intensity employed, 1300 C.G.S., produces an elongation and not a contraction as observed."

The publication of More's paper led to a discussion‡ in which several well known physicists took part; but the views expressed were by no means concordant, and I believe that at the present time it is not agreed whether there is in fact any such mechanical stress; whether, supposing one to exist, it is compressive or tensile, and whether it is "Maxwell's stress" or some other. The compressive stress which I contemplated was, of course, quite unconnected with Maxwell's theory of stress in the electro-magnetic field, and the expression employed for its value was based upon principles which were well known long before the date of Maxwell's work.§

Several papers have been more recently published‖ in which the

* 'Phil. Mag.,' vol. 29, p. 440, 1895. The difference due to the term $H^2/8\pi$ is, when $H = 500$, 0·05 per cent.; when $H = 900$, 0·16 per cent.; and when $H = 1400$, 0·35 per cent.

† 'Phil. Mag.,' vol. 40, p. 345, 1895.

‡ 'Nature,' vol. 53, pp. 269, 316, 365, 462, 533.

§ The magnetic force inside a narrow transverse gap in a longitudinally magnetised bar is $B = H + 4\pi I$. Supposing one portion of the bar to be fixed, the force acting upon the face of the other portion is less than B by $2\pi I$, the part due to the face itself; thus the attractive force per unit area $= (B - 2\pi I) \times I = 2\pi I^2 + HI$. The stress between any two portions of a magnetised bar, divided by an imaginary transverse plane, is sustained by the intermolecular springs, whatever their physical nature may be, to which the elasticity of the metal is due.

‖ Klingenberg, 'Rostock Univ. Thesis,' Berlin, 1897; Brackett, 'Phys. Rev.,' vol. 5, p. 257, 1897; Rhoads, *loc. cit.*

writers insist upon the necessity of correcting curves of magnetic strain for mechanical stress. Brackett attributes the recognition of this necessity to Rowland, who, he says, defended his position as follows :—The compressive force which will tend to close up a very thin air gap in a divided magnet must exist in any magnet, for according to all our ideas of matter there is no real difference in the case where the air gap exists and where it does not, because we must still consider the gaps between the molecules.

I venture to think that the results of my thermoelectric experiments with iron and nickel afford strong evidence of the reality of the mechanical stress in question. Before any comparison is possible between the two phenomena of change of length and change of thermoelectric power, considered as due to the molecular effects of magnetisation, it is clear that the effect of any extraneous mechanical action tending to alter the length of the metal must be eliminated. The stress under discussion, if it exists, is for our present purpose no less an extraneous one than if it were produced by loading the metal with a weight. Conjecturing that there might be a relation between the thermoelectric and the strain effects of magnetisation, I plotted curves for the two phenomena side by side (see curves (D) and (*b*), fig. 4); but although these curves bear a superficial resemblance to each other, it is clear that the phenomena to which they relate are by no means in correspondence. In particular, one curve cuts the axis at an early stage, indicating a reversal of sign, while the other appears to become asymptotic. Curve (*d*) which is drawn to the same scale as curve (*b*) indicates, in ten-millionths of length, the correction to be made in respect of the hypothetical compression due to mechanical stress; its ordinates are proportional to P/M, P being the greatest weight which (as found experimentally) could be lifted when the iron was magnetised by the corresponding field, M being Young's modulus. Adding together curves (*b*) and (*d*), we get the "corrected" curve (E), which, as will be seen, coincides with the thermoelectric curve (D) as nearly as could be expected under the conditions of the experiments.

Still more striking is the case of the wire under tension, curves (F) and (*f*) fig. 5. Here there is not even a superficial resemblance; the curve for change of length is an almost straight line inclined to the horizontal axis and lying entirely below it, while the thermoelectric curve begins above the axis and crosses it at H = 450. By making the same addition for stress as in the former case, curve (*d*) being again employed for the purpose, we obtain a corrected curve of length, indicated by the crosses on curve (F), which, when the ordinates are plotted to a suitable scale, closely follows the thermoelectric curve (F), and would, if it were continued a little farther,* evidently meet the axis at just the same point.

* All the curves for change of length referred to in this paper have appeared in

So far the presumption in favour of the reality of the compressive stress appears to be fairly strong, but it is, I think, greatly strengthened by the results obtained for nickel. In fig. 7 (L) and (k) are curves of change of thermoelectric power and of change of length for this metal. There is obviously a strong likeness between the two, though they lie on opposite sides of the axis. Curve (n) is derived from (k) simply by inverting the latter and plotting the ordinates to a slightly different scale. The inverted curve is seen to be throughout its whole length almost a counterpart of the thermoelectric curve; and this although it has not been "corrected" for compressive stress. Why then should the correction which is indispensable for iron be unnecessary for nickel? The answer is that while for iron the calculated correction for mechanical stress is relatively very considerable, for nickel it turns out to be very small, so small as to be negligible. The changes of length indicated by the compression curve for iron, (d), fig. 4, are generally much greater than those indicated by the curve (b), to which the correction is to be applied; and the two curves have very different forms. On the other hand the compression curve for nickel (m), fig. 7, is an almost straight line making a very small angle with the axis of H, the changes of length which it indicates amounting to not more than 2 or 3 per cent. of the changes exhibited by the uncorrected curve for corresponding fields. Both curves, moreover, rise gradually from the origin to their highest points. Thus it happens that the uncorrected and the corrected curves for nickel, if referred respectively to scales of ordinates so chosen that the two curves may be of the same height, are sensibly identical. Curve (n) may be regarded either as the uncorrected or as the corrected curve, according as the ordinates are referred to the scale given in the right-hand margin or to a different scale in which each unit is very slightly increased.

Thus the absence of any need for the correction in the case of nickel where *a priori* it ought not to be required, tends to show that the success of its application in the case of iron is not a mere accident, and that the compressive stress is consequently a *vera causa*.

Apparatus and Methods of Experiment.

Two methods of experiment were employed. In the one the thermoelectric force of the magnetisable metal in conjunction with copper was opposed by a similar couple in which the first metal was unmagnetised; in the other it was opposed by an electromotive force derived from a battery.

The arrangement adopted for *Method I* is shown diagrammatically in

former communications to the Royal Society. It is unfortunate in the present connection that some of the experiments were not carried further.

fig. 1, which, for the sake of clearness, is not drawn to scale. AB is a compound rod made by soldering together end to end five straight wires in the order (1) copper, (2) iron (or other magnetic metal), (3) copper, (4) iron, (5) copper. The length of each iron wire M, N, is 10 cm., and that of the copper wire between them 12 cm. The middle and end portions of the rod are surrounded by three separate brass tubes, in the sides of which are inlet pipes, C, G, H, D, and outlet pipes, E, K, F, for the admission and egress of water and steam. The

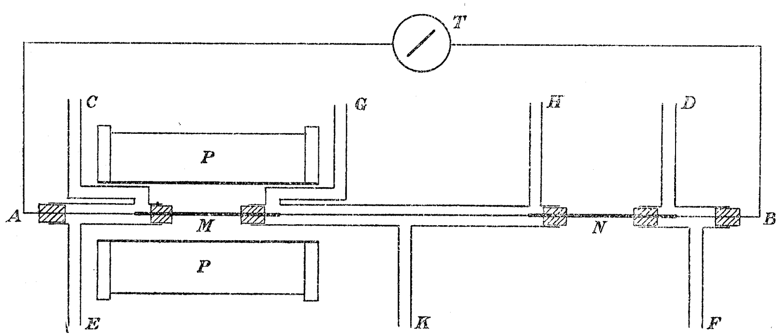

FIG. 1.

rod is held axially in the tubes by well-tallowed corks, through which it passes, each of the four copper-iron junctions being exactly opposite an inlet. Cold water enters at C and D and emerges at E and F; steam from a small boiler is admitted at G and H, escaping at K. It was ascertained experimentally that with the low resistances and small electromotive forces employed water was a good insulator. The iron wire M is magnetised by the coil PP. The field at N due to the coil is less than a hundredth part of that in the interior of the coil, and is regarded as negligible; but if the apparatus were to be reconstructed, I should, with my present experience, consider it desirable to increase the distance between M and N. The two ends of the compound rod AB were joined to a galvanometer T of low resistance.

Method II is diagrammatically illustrated in fig. 2. AB consists of a wire or strip of the magnetic metal M soldered between two copper wires; it passes through two short and wide brass tubes provided with corks at their ends. Inlet and outlet tubes are fitted to the corks, as shown in the diagram, C admitting cold water and G steam. Cold water also flows through D, F, to equalise the temperatures at A and B. The electromotive force of the thermo-couple is opposed by the potentiometer arrangement shown. S is a dry cell having an electromotive force of 1·46 volt. The low resistance r was either 10 or 2 ohms.; the high resistance R ranged from some hundreds to some thousands of ohms in the different experiments. Before an experiment

was begun, R was adjusted until the galvanometer T showed no deflection when the circuit was closed, though a small permanent

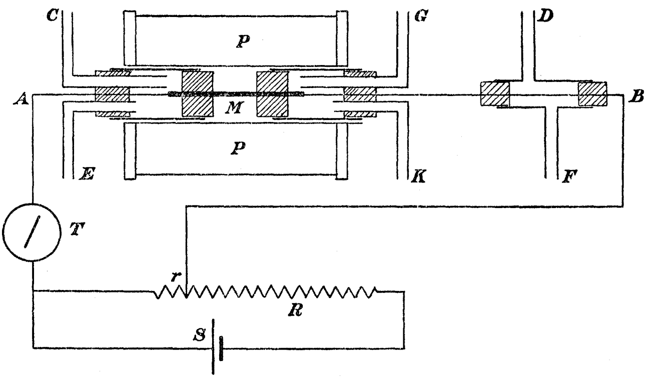

FIG. 2.

current was really of no consequence. The deflection (or increase of deflection), which occurred when M was magnetised was thus entirely due to the change of thermoelectric force by magnetisation.

The aperiodic galvanometer T, which was placed at a distance of 3·5 metres from the magnetising coil, is of the form designed by Ayrton and Mather; the resistance of its moving coil together with the suspension is 4·70 ohm. In most of the experiments the distance between the mirror and the scale was 12 feet (3·66 metres), when the deflection for 1 microampère was found to be 54 scale divisions of $\frac{1}{40}$th inch (0·0645 cm.).

Two magnetising coils were used; one is 11·5 cm. in length and contains 876 turns of No. 18 wire, the field near the middle of its interior due to 1 ampère being 92 units. The length of the other is 20·4 cm., and the number of turns of wire 2,770; 1 ampère produces a field of 174 units in its interior. The magnetising current was derived from a battery of 27 storage cells and was measured by a moving-coil ammeter, reading from 0—15 ampères by tenths. The ammeter was calibrated by comparison with a tangent galvanometer, and the readings were found to be sufficiently accurate for the purpose in view. Currents of more than 15 ampères were measured by the engine-room ammeter; but on account of their excessive heating effect such strong currents were used in only a few of the experiments.

The Experiments.

Iron.—The results of experiments with two different samples of iron and one of steel are shown by curves (A), (B) and (C) in fig. 3, where the ordinates are proportional to the temporary increase of

thermoelectric force produced by the application of the corresponding external field H. Curve (A) relates to a specimen of iron wire

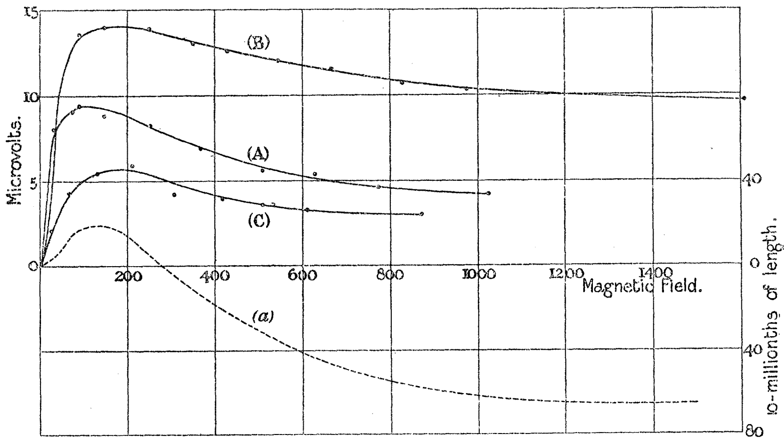

Fig. 3.—Curves (A), (B), and (C) show changes of thermoelectric force for pure iron, commercial iron, and steel respectively. Curve (*a*) shows corresponding changes of length for iron.

0·28 mm. in diameter, supplied by Messrs. J. J. Griffin and Sons as pure. Details of the experiment are given as an example of the manner of working:—

Method II.—R = 14,000; r = 10 ohms.
Coil No. 1.—H = ampères × 92.
Temperature of cold water, 14° C.

Resistance of galvanometer	4·70	ohms.
" leading wires	0·39	"
" potential coil	10·0	"
" thermo-rod	0·20	"
Total resistance in circuit ...	15·29	"

Electromotive force of 1 microvolt gives 1/15·29 microampères = 54/15·29 scale divisions, or deflection in scale divisions × (15·29/54 =) 0·283 = microvolts.

Before every observation the iron was demagnetised by Ewing's method of reversals, alternating currents gradually decreasing to zero being switched into the magnetising coil.

The difference of the temperatures of the water at 14° and of the steam at 100° was 86°; assuming that the actual temperatures of the junctions were respectively $\frac{1}{2}$° above and below those of their surroundings, the change of thermoelectric power for a given field

may be found by dividing the change of microvolts by 85. In all the experiments the temperature of the cold water differed little from 14°, the mean temperature being therefore 57°.

Table I.

Ampères.	Galvanometer deflections.	Mean.	H = ampères × 92.	Microvolts deflections × 0·283.
0·35	28, 28, 28, 29	28·3	32	8·0
0·8	31, 33, 34, 32, 32	32·2	74	9·1
1·0	34, 33, 33, 33, 34	33·3	92	9·4
1·6	31, 32, 31, 31, 30	31·0	147	8·8
2·6	29, 29, 29	29·0	249	8·2
4·0	24, 24, 25	24·3	368	6·9
5·5	20, 19, 20	19·7	506	5·6
6·8	19, 19, 19	19·0	626	5·4
8·4	16, 17, 16	16·3	773	4·6
11·1	15, 15	15·0	1020	4·2

Curve (B) was given by a piece of commercial iron wire, which was hard, springy, and easily broken. Changes of thermoelectric force, like changes of length, are greater for such a specimen than for one which is purer and softer.

Curve (C) shows the results for a piece of steel knitting needle in the state in which it was bought. The experiment was repeated with the wire in a glass hard state, but the curve was almost unchanged.

The dotted curve (*a*), copied from a former paper,* shows for comparison the changes of length exhibited by an iron wire in fields up to 1500. The main point of difference is that whereas the curve for change of length crosses the axis of H, indicating a reversal of the sign of the phenomenon in moderate fields, the other does not. Two other thermoelectric experiments, made with different pieces of iron, gave results of a like character. Even with the high field of 1600, which greatly exceeds any before used in similar work, there is no indication that a reversal of sign would ever be reached.

The curves in fig. 4 are intended to show the effect of "correction" for mechanical stress. The pieces of wire used in the three experiments concerned were all cut for the same hank, and imperfectly annealed by heating in a Bunsen flame. Curve (D) is the thermoelectric curve for the sample, and (*b*) the curve of elongation and retraction.† Curve (*c*) shows the relation of lifting power to field,‡ the ordinates being referred to the scale of grammes weight on the

* 'Phil. Trans.,' vol. 179, p. 228, fig. 6, 1888.

† *Loc. cit.*, p. 224, fig. 5.

‡ 'Roy. Soc. Proc.,' vol. 40, p. 491, fig. 1, 1886.

right-hand margin of the diagram. Curve (d) indicates the contraction in ten-millionths of length due to the mechanical compression, and is derived from (c) as follows:—If P = the weight supported per

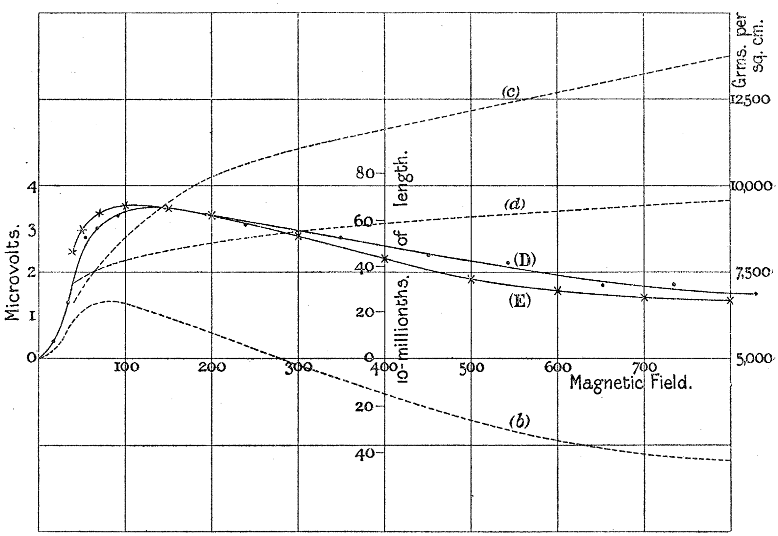

FIG. 4.—(D) shows change of thermoelectric power; (b) change of length; (c) lifting power; (d) mechanical compression, deduced from (c). (E) = (b) + (d), and is the "corrected" curve of change of length.

square centimetre for a given value of H, as shown in (c), and M = Young's modulus in grammes weight per square centimetre, the mechanical contraction in ten-millionths = $P \times 10^7/M$. The value of M is taken as 2×10^9. (It might without sensibly affecting the form of the curve have been $1{\cdot}9 \times 10^9$ or $2{\cdot}1 \times 10^9$, and its actual value no doubt comes within these limits.) Hence, $P \times 10^7/M = P/200$, or the mechanical contraction in ten-millionths is numerically equal to the grammes weight supported divided by 200; ordinates of curve (d) are therefore simply P/200. In the following table values of P are obtained by measuring ordinates of curve (c); elongations and retractions (E) are similarly derived from the published original of curve (b).*

Ordinates of the three curves (b), (d), and (E) are referred to the scale of ten-millionths given in the middle of the diagram. For the sake of easy comparison this scale was so chosen that the heights of the thermoelectric and the corrected elongation curves (D) and (E) are about equal. As before remarked, the close agreement between the

* *Loc. cit.*

Table II.

P = tractive force. E = elongation.

H.	P.	P/200.	E.	P/200 + E.
40	6,550	33·0	12·0	45·0
50	7,000	35·0	20·0	55·0
70	7,700	38·5	24·0	62·5
100	8,500	42·5	23·0	65·5
150	9,500	47·5	17·0	64·5
200	10,250	51·0	10·0	61·0
300	11,100	55·5	− 2·5	53·0
400	11,600	58·0	−15·0	43·0
500	12,200	61·0	−27·0	34·0
600	12,700	63·5	−35·0	28·5
700	13,200	66·0	−40·0	26·0
800	13,700	68·5	−44·0	24·5

curves can hardly be the result of accident, the less so as the same similarity is manifested under different conditions.

Tension has the effect of lowering the elongation curve of iron, the maximum becoming smaller and contraction beginning at an earlier stage of the magnetisation. If the tension is great there is no preliminary elongation at all, and the wire begins to contract with the smallest magnetising forces. Curves (*e*) and (*f*), fig. 5,* show the

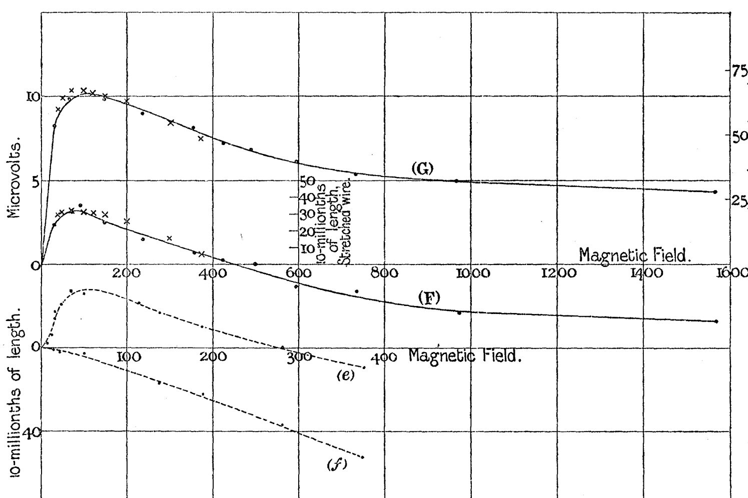

FIG. 5.—Curve (G) shows changes of thermoelectric force for an unstressed iron wire; (F) same when the wire was loaded with 1620 kilogrammes per sq. cm. Curves (*e*) and (*f*) show changes of length for iron loaded with 351 and 1600 kilogrammes. Crosses on (F) and (G) indicate (*e*) and (*f*) corrected for mechanical stress.

* 'Roy. Soc. Proc.,' vol. 47, p. 474, fig. 2, 1890.

changes of length undergone by an iron wire when loaded with weights of 351 and 1600 kilogrammes per sq. cm., the curve for the first-named load being practically the same as for an unloaded wire. Curves (F) and (G) indicate the changes of thermoelectric force with field for an iron wire, first when loaded with 1620 kilogrammes per sq. cm., and afterwards without load, the points of observation being marked by dots. The crosses on (G) and (F) indicate the course of the curves (*e*) and (*f*) after correction for mechanical stress; the correspondence is so close that it was impracticable to draw the corrected curves separately. The vertical scale of the corrected curves is not the same in the two cases; that for the upper one is given in the right-hand margin, and that for the lower in the middle of the diagram. Data for the construction of these curves were obtained in the same manner as before, and are given in the annexed table:—

Table III.

P = tractive force in grammes per sq. cm. E = elongation.

H.	P.	P/200.	E, Curve (*e*).	E, Curve (*f*).	P/200 + E, Curve (*e*).	P/200 + E, Curve (*f*).
40	6,550	33·0	26	− 3	59·0	30·0
50	7,000	35·0	28	− 4	63·0	31·0
70	7,700	38·5	27	− 6	65·5	32·5
100	8,500	42·5	23	−11	65·5	31·5
120	9,000	45·0	20	−14	65·0	31·0
150	9,500	47·5	16	−18	63·5	29·5
200	10,250	51·0	10	−25	61·0	26·0
300	11,100	55·5	− 2	−40	53·0	15·5
375	11,500	57·5	−10	−52	47·5	5·5

It is to be noted that the three sets of experiments—for change of thermoelectric force, change of length, and lifting power—were made with three different samples of iron wire.

The effect of annealing upon the changes of length and of thermoelectric force is illustrated in fig. 6. Curve (*g*) shows the elongation of a wire in the state in which it was bought,* while (*h*) indicates its behaviour after it had been carefully annealed. This operation was performed by enclosing the wire in an iron tube which was placed in a hot fire and allowed to cool gradually as the fire died out. Curve (H) shows the changes of thermoelectric force in a piece of the same kind of wire when in its original state, and (K) the modification which resulted from heating the wire to redness in a Bunsen flame and cooling it in air. In both cases the effect of annealing is to depress the curve.

* 'Roy. Soc. Proc.,' vol. 55, p. 230, fig. 1, 1894.

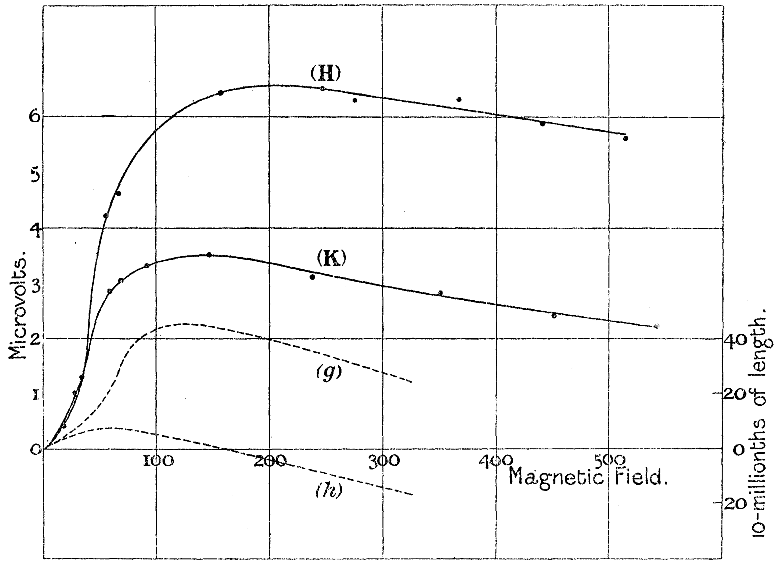

FIG. 6.—Curve (H) shows changes of thermoelectric force in an unannealed iron wire; (K) changes in the same wire when annealed. Curves (*g*) and (*h*) show changes of length in another wire when unannealed and after annealing.

A glance at any of the curves of thermoelectric force for iron will show how easily errors might arise if it were assumed that a wire which had been subjected to a magnetic field became perfectly demagnetised when the field was withdrawn. In all my experiments the curves would have been much lower but for the demagnetisation by reversals before every observation. The dimensional ratio of the short wires which I used was generally so small, and the self-demagnetising consequently so great, that an apparent reversal of thermoelectric force in strong fields did not often occur. But in the case of a wire 17·5 cm. in length and 0·026 cm. in diameter, this spurious reversal appeared in fields above 500. When the *demagnetised* wire was subjected to a field exceeding this strength, there occurred a galvanometer deflection to the right, indicating a genuine increase of thermoelectric force; but when the magnetising current was interrupted, the spot of light, instead of going back again, went still further to the right, the thermoelectric force due to the residual magnetism being greater than that due to the strong field. When the magnetising circuit was again closed before the wire was demagnetised, the spot of light, of course, moved to the left, and if the residual magnetism were disregarded, it would naturally be supposed that a reversal of thermoelectric force was indicated. The spurious reversal was also very conspicuous in the case of the steel wires.

Nickel.—Since the effect of magnetisation upon a nickel rod or wire is to shorten it, while, if the "correction" be admissible, iron is always lengthened by magnetisation, it was to be expected from analogy that the effects upon thermoelectric power would be opposite in iron and in nickel. In iron the thermoelectric power of the magnetised with respect to the unmagnetised metal is positive; in nickel, therefore, it should be negative. This view, though in accordance with what is generally accepted as the fact, is, however, at variance with the results of all my experiments.

Five different samples of nickel were used, curves for four of these (L), (M), (N), (O), being given in fig. 7.

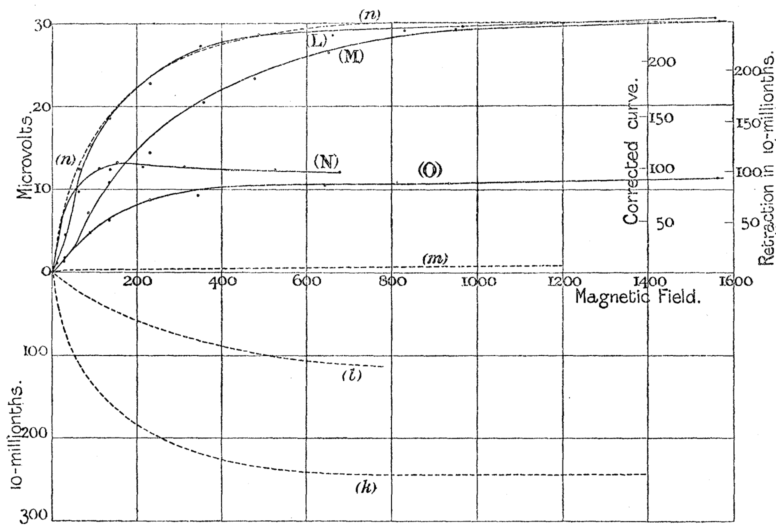

FIG. 7.—Curves (L) and (M) show changes of thermoelectric force for pure nickel; (N) and (O) the same for impure nickel. Curves (k) and (l) give changes of length, and correspond to (L) and (O); (m) shows mechanical compression; the dotted curve (n) is (k) inverted and plotted to the scale of ordinates in the right-hand margin.

Curve (L) relates to a piece of thick wire 2·95 mm. in diameter, bought of Messrs. Johnson and Matthey as pure. The retraction curve* for another piece of the same wire is that marked (k).

Curve (M) was given by a wire 0·65 mm. in diameter; this was also supplied by Messrs. Johnson and Matthey, and described as being "as pure as conveniently possible."

Curve (N) shows the result of an experiment with a sample of wire supplied by Messrs. J. J. Griffin and Sons, which did not purport to be pure and probably contains a considerable proportion of iron.

* 'Phil. Trans.,' vol. 179, p. 228, fig. 6, 1888.

Curve (O) was obtained from a strip about 1·4 mm. wide and 0·75 mm. thick, which was cut from a rolled sheet purchased at a metal warehouse. Curve (*l*) shows the retraction of a strip of the same metal 9 mm. in width.*

The fifth specimen was a wire taken from a piece of nickel gauze. With this, too, the magnetised was found to be always thermoelectrically positive to the unmagnetised metal.

[A sixth specimen, consisting of a wire 3·5 mm. in diameter, has been recently tested, with the same result.—*May* 23, 1904.]

The form of curve (N) which rises to a maximum at about H = 150 suggested a possible source of error by which Thomson may have been misled, and I therefore repeated his experiment. The arrangement which is shown in fig. 8, is essentially the same as that employed by Thomson. A piece of Griffin's impure wire was bent into the shape of a horse-shoe, as shown, one of the limbs passing through the small magnetising coil, PP; the ends of the horse-shoe were connected by brass binding-screws to wires leading to the galvanometer T. Heat was applied at or near Q by touching the wire with a hot copper rod, and when the magnetising circuit was closed, the galvanometer T indicated a thermo-current which usually had the same direction as in the other experiments—from unmagnetised to magnetised through hot. It

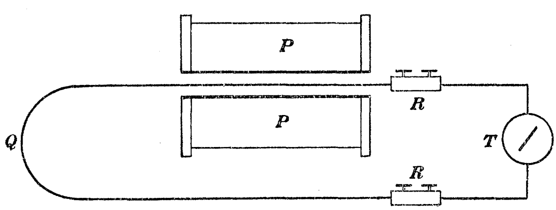

FIG. 8.

was, however, found possible to adjust the strength of the field and the position of Q so that a thermo-current flowed in the opposite direction. This was the case, for example, when the field-strength was 400 and the distance of Q from the coil 8 cm. If a slight change were made in the position of Q, the application of the same field again produced a current in the normal direction. This deceptive effect, which, of course, really occurred between more strongly and less strongly magnetised portions of the metal, could not be obtained with the pure nickel wire, nor with the wire taken from the gauze, which were the only other specimens tested. With an iron wire, however, it was quite easily produced.

Curve (*m*), fig. 7, shows in ten-millionths of length the mechanical compression due to magnetisation; in comparison with that for iron,

* *Loc. cit.*, p. 214, fig. 4.

curve (*d*), fig. 4, it is seen to be quite insignificant. Since no experiments have been made to determine the lifting-power of nickel, this was calculated from the expression $(2\pi I^2 + HI)/g$. Values of I were obtained from a table given by Ewing, based upon results of an experiment by Du Bois;* the specimen used was an ovoid instead of a cylindrical wire, but the values might be increased or diminished by 10 per cent. without influencing the corrected curve to any appreciable extent. Young's modulus M was taken as $2\cdot2 \times 10^9$, approximating 2175×10^6, the value found† for nickel by H. Tomlinson; this also need not be very accurately known for the present purpose. Table IV shows how the ordinates of the compression curve (P/220), and those of the corrected curve (R - P/220), were determined.

Table IV.

$P = (2\pi I^2 + HI)/g$. $C = P \times 10^7/M = P/220$. R = retraction in ten-millionths.

H.	I.	P.	C.	R.	R – C.
100	313	659	3·0	136	133
200	375	977	4·5	181	177
300	406	1180	5·3	210	205
400	428	1348	6·1	224	218
500	441	1470	6·7	232	225
600	450	1572	7·1	239	232
700	456	1657	7·5	242	234
800	459	1724	7·8	244	236
1200	471	1997	9·0	245	236

Curve (*n*) which nearly coincides with the thermoelectric curve (L) is the uncorrected retraction curve (*k*) inverted and plotted to the scale of ordinates in the right-hand margin. If the corrected curve were plotted to the slightly different scale just within the margin, it would be substantially identical with (*n*), which may therefore be regarded as representing either the corrected or the uncorrected curve of change of length.

The small difference noticeable in the forms of the two curves (O) and (*l*) for the two nickel strips is just such as would be caused by the difference between their dimensional ratios.

As to the curves in fig. 9, which show a remarkable qualitative correspondence with regard to the complex effects of tensile stress, nothing need be added to what has already been said. The dotted curves‡ are of course inverted.

* 'Magnetic Induction,' 3rd edit., p. 164.
† 'Roy. Soc. Proc.,' vol. 37, p. 390, 1884.
‡ 'Roy. Soc. Proc.,' vol. 47, p. 475, fig. 3, 1890.

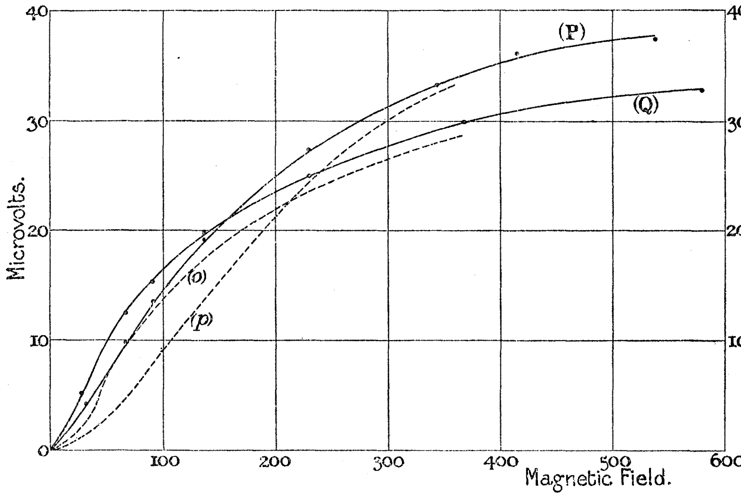

FIG. 9.—Curves (P) and (Q) show changes of thermoelectric force in an annealed nickel wire when loaded respectively with 970 and 447 kilogrammes per sq. cm. Curves (*o*) and (*p*) show changes of length for an unannealed wire when loaded with 980 and 420 kilogrammes per sq. cm.

Cobalt.—Experiments are made with two different specimens of cobalt, the results being given in fig. 10.

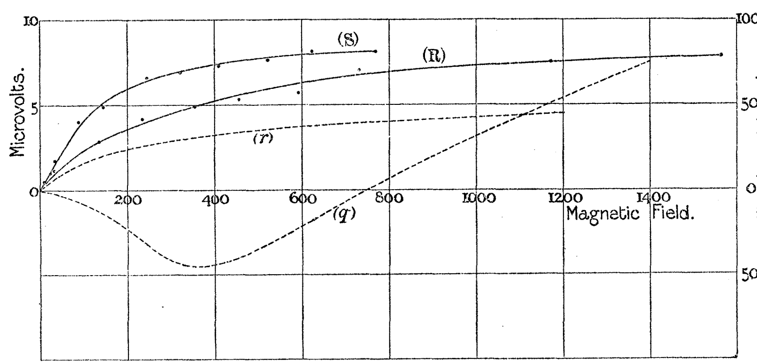

FIG. 10.—(R) and (S) show thermoelectric changes for cast and rolled cobalt respectively; (*q*) shows changes of length for the cast cobalt; (*r*) is the curve of mechanical compression.

Curve (R), showing thermoelectric changes, relates to a cast rod supplied by Messrs. Johnson and Matthey; the change of length curve (*q*) was obtained with another piece of the same rod.*

This latter curious curve is quite unlike the thermoelectric curve (R),

* 'Phil. Trans.,' vol. 179, p. 228, fig. 6, 1888.

and evidently cannot be made to resemble it by applying the correction for mechanical compression. The compression curve (r) was constructed, like that for nickel, from values of I furnished by Ewing; Young's modulus was taken as 2×10^9, the value found by Tomlinson* for unannealed cobalt being 2005×10^6.

The thermoelectric curve (S) was given by a strip of rolled cobalt, for which I am indebted to the kindness of Messrs. Henry Wiggin and Co., of Birmingham. It is of interest as indicating the similar behaviour of a very different sample of the metal.

If there is any relation between the thermoelectric and the strain phenomena in cobalt, it is obviously disguised by some cause which has yet to be discovered.

[*Note added May* 23, 1904.—Some further experiments have been made with specimens of cobalt which had been very thoroughly annealed. For cast cobalt the change-of-length curve is entirely altered by annealing, becoming, at least in fields up to 1360 units, a straight line represented by $R = 0{\cdot}056H$, where R is the retraction in ten-millionths. The thermoelectric curve is considerably lowered, but in other respects is not much affected. No relation between the thermoelectric and the strain phenomena could be traced.

From an examination of the curves in fig. 10 it appears that the thermoelectric power of the unmagnetised with respect to the magnetised cast cobalt is proportional to the compressive stress, and consequently to the square of the magnetic induction.]

* 'Roy. Soc. Proc.,' vol. 39, p. 530, 1885.